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FIG. 1 is a block diagram of a laser scanning system. The system includes a control computer (38) connected to a stepping table (16) and a scanner. The control computer sends signals (86, 87) to two galvanometers (30, 32) and receives feedback signals (88, 89). A light integrator (94) receives input from a photo diode (92) and sends a signal (60) to a laser (12). The laser beam passes through a tuning and line-narrowing assembly (54) and is reflected by a mirror (64) to a detector (24). A wavemeter (70) is used for wavelength measurement, and a photodiode (72) is used for feedback. The system is mounted on a base (10) with a coordinate system (X, Y, Z).

A deep-UV photolithography system includes a narrow-bandwidth pulsed excimer laser illumination source (12) and an all-fused-silica lens assembly. The system is capable of line definition at the 0.5-micrometer level. One significant feature of the system is its ability to perform wafer focus tracking by simply changing the frequency of the laser.

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- 1 -

## DEEP-UV LITHOGRAPHY

Background of the Invention

This invention relates to optical lithography and, more particularly, to apparatus and methods for achieving short-wavelength optical lithography adapted for fabricating high-quality fine-line semiconductor devices.

It is known that the resolution limit ( $L_{\min}$ ) for equal lines and spaces in an optical imaging system can be expressed as

$$L_{\min} = K\lambda/NA \quad (1)$$

where K is a constant whose value is typically between 0.4 and 1.0 depending on processing and illumination conditions and resist characteristics,  $\lambda$  is the wavelength of the exposing radiation and NA is the numerical aperture of the projection optics.

It is apparent from (1) that the minimum printable feature can be reduced by decreasing  $\lambda$  or by increasing NA. But, since the depth of focus of the system varies inversely as  $(NA)^2$ , it is usually preferable in a practical high-resolution system to achieve the desired  $L_{\min}$  by reducing  $\lambda$  rather than increasing NA.

The present invention is directed to a novel short-wavelength lithograph system.

Summary of the Invention

A lithograph system according to the invention includes a narrow-bandwidth tunable laser operating at a wavelength in the deep-UV range. A monochromatic all-fused-silica lens assembly is utilized to direct the output of the laser to successive portions of the surface of a resist-coated wafer mounted on a movable support, e.g., a known "stepping table".

The combination of a narrow-bandwidth laser and a monochromatic lens assembly in accordance with the invention makes it possible to quickly and easily accomplish focus tracking in the system. This is done

- 2 -

by directing the output of a laser onto the surface of a workpiece via a projection lens and controlling the wavelength of the laser to maintain the focal length of the lens equal to the lens-to-workpiece surface spacing.

5 Other features of the system are described hereinafter.

#### Brief Description of the Drawing

FIGS. 1 and 2 taken together schematically depict an apparatus in accordance with the invention for achieving short-wavelength optical lithography; and

10 FIG. 3 shows in more detail a particular implementation of a portion of FIG. 1.

#### Detailed Description

The invention is described in connection with a known type of "step-and-repeat" lithographic system.

In accordance with one feature of the invention, a laser illumination source is physically separated from the movable table portion of the system. Thus, for example, the equipment 10 including laser 12 shown in FIG. 1 is advantageously located at a site removed from the equipment 14 including stepping table 16 shown in FIG. 2. In this arrangement, the laser beam provided by the equipment 10 is propagated through air or controlled space to the equipment 14, as indicated by arrow 18 in FIG. 1. (Actually, as will be clear later below, two coaxially disposed laser beams are transmitted from the equipment 10 in the direction of the arrow 18. One beam constitutes the exposing radiation. The other beam is utilized only for alignment control purposes.)

30 There are several reasons for physically separating the aforementioned equipments 10 and 14. In some cases, for example, the laser 12 shown in FIG. 1 includes a toxic constituent which for safety considerations should be located at a site remote from operating personnel.

35 In operation, the stepping table moves successive portions of a resist coated semiconductor wafer 40 into the

- 3 -

path of the illuminating radiation. In the past, after each indexing of the table, a delay was necessary to allow damping out of vibrations caused by the table movements before the illuminating beam was turned on. This is time consuming.

In accordance with a feature of the invention, instrumentalities are provided in the equipments 10 and 14 for instantaneously moving the laser beams in conformity with the vibrations in the table 16 for maintaining the laser beams 18 aligned relative to the table. Thus, after each indexing of the table, the beam can be more quickly turned on. Illustratively, these instrumentalities include standard driven galvanometer mirrors 20 and 22 in the equipment 10 and a conventional quadrant photodetector or position-sensitive photodetector 24 mounted on the table 16. Electrical signals provided by the array 24 are applied to differential amplifiers 26 and 28 in feedback loops that respectively control galvanometer motors 30 and 32. The motor 30 is mechanically coupled to the mirror 20 via a Y-axis-parallel shaft 34, and the motor 32 is coupled to the mirror 22 via a Z-axis-parallel shaft 36. By selective rotation of the mirrors 20 and 22, the orientation of the laser beams 18 emanating from the equipment 10 is varied in a controlled manner to compensate for vibratory movement of the table 16.

Under quiescent conditions, the desired orientation of the laser beams 18 relative to the table 16 is established by steady-state signals applied to the galvanometer motors 30 and 32 from a control computer 38. The additional variable signals supplied by the differential amplifiers 26 and 28 to the motors 30 and 32 are superimposed on the steady-state signals supplied by the computer. This process is described further hereinafter.

Each of the lenses included in the equipment 14 of FIG. 2 is made only of fused silica. Fused silica is a highly stable material that is highly transparent to short-

- 4 -

wavelength light. Moreover, fused silica can be fabricated with good precision to form specified lens designs.

Despite these apparent advantages, applicant is the first to have proposed the use of a single optical material

5 (fused silica) to make a high-quality lens assembly for short-wavelength (for example, deep-UV) optical lithography based on laser illumination. Heretofore, it has been customary to fabricate lenses utilizing multiple materials to correct for chromatic aberrations.

10               Once he designed an all-fused-silica lens assembly, applicant recognized that a laser source to be combined with the assembly must as a practical matter have an extremely narrow bandwidth if chromatic aberrations in the single-optical-material assembly were to be avoided.

15 Since chromatic aberrations are unavoidable with a single-optical-material design, if the laser source bandwidth is not suitably narrow, the projected image on the laser-beam-illuminated wafer 40 (FIG. 2) would be unacceptably blurred.

20               But applicant found that all suitable short-wavelength laser sources of adequate power were pulsed lasers that inherently exhibit excessively broad bandwidths. At that point, the obvious thing to have done, as other workers in the art have, would have been to

25 redesign the lens assembly to be free of chromatic aberrations with the available source bandwidths. But this would have entailed employing optical materials other than only fused silica. Instead, applicant embarked on the unobvious course of retaining an all-fused-silica lens

30 design and redesigning the laser source to exhibit an appropriately narrow bandwidth. This unique approach allows the realization of a superior lens design and, moreover, is the basis for achieving electronic focus tracking as well as for achieving electronic tuning of the

35 laser source. Such tuning allows the source to be matched to the operating characteristics of the lens assembly, as will be specified in detail later below.

- 5 -

Illustratively, the laser 12 included in the equipment 10 of FIG. 1 comprises an excimer laser. This category of lasers is capable of UV emission at wavelengths from, for example, below 4000 Å to below 2000 Å.

Excimer lasers and their application to lithography are described in a number of publications. These include: "Laser Projection Printing" by G. M. Dubroeuq et al, Proceedings of Microcircuit Engineering Conference, Aachen, Germany, September 1979, pages 328-337; "Applications of Excimer Lasers in Microelectronics" by T. McGrath, Solid State Technology, December 1983, pages 165-169; "Deep UV Exposure of Ag<sub>2</sub>Se/GeSe<sub>2</sub> Utilizing an Excimer Laser" by K. J. Polasko et al, IEEE Electron Device Letters, Vol. EDL-5, No. 1, January 1984, pages 24-26; and "Excimer Laser Projection Lithography" by K. Jain et al, Applied Optics, Vol. 23, No. 5, March 1, 1984, pages 648-650.

By way of example, the laser 12 of FIG. 1 comprises a pulsed KrF gas excimer laser designed to operate at a nominal center wavelength of 2484 Å. (The fluorine constituent in KrF is highly toxic.) Illustratively, the pulse repetition rate of the laser 12 is selected to be approximately 1000 pulses per second.

Inherently, the KrF excimer laser 12 (FIG. 1) has a spectral bandwidth at the half-power point of approximately 10 Å. But, recognizing that an all-fused-silica lens assembly for high-resolution lithography requires a source bandwidth of less than about 0.1 Å to be free of chromatic aberrations, applicant combined a bandwidth-narrowing assembly with the laser 12 to achieve an output at 2484 Å characterized by a half-power-point bandwidth of only approximately 0.05 Å. At a repetition rate of 1000 pulses per second, the power of each such pulse is about 5 millijoules, which characteristics provide an adequate basis for uniform high-resolution high-throughput

- 6 -

lithography.

Various techniques are available for narrowing the inherent bandwidth of the laser 12. One suitable assembly for doing this is shown in FIG. 3 (the figure also showing portions 42 and 44 of the laser). Beam 46 emanating from the laser propagates through a standard low-finesse etalon 48 and impinges upon a conventional grazing-incidence grating 50 which is spaced apart from a facing high-reflectivity mirror 52. Illustratively, the grating 50 has 3000-to-4000 grooves per millimeter. The elements 48, 50 and 52 constitute both a tuning and a bandwidth narrowing assembly. This assembly is shown in FIG. 1 and identified therein by reference numeral 54 ("bandwidth narrowing" is also referred to in the art as "line-narrowing").

The desired narrow-bandwidth output emanates from assembly 54 and propagates in the direction indicated by arrow 55 in FIG. 3. The arrow 55 is also shown in FIG. 1 wherein it is oriented parallel to the X axis.

The assembly 54 also provides a means for establishing the center wavelength of the laser output 55 at a predetermined value and thereafter precisely maintaining the wavelength at that value (or purposely moving the wavelength off that value to accomplish electronic focus tracking). This is accomplished by rotating any one or combination of the elements 48, 50 and 52 about an axis perpendicular to the plane of the paper on which FIG. 3 is drawn. For coarse tuning, rotating the mirror 52 and/or the grating 50 is satisfactory. For fine tuning, rotating only the etalon 48 is effective. In practice, it is usually advantageous to initially establish the predetermined center wavelength by rotating one or both of the elements 50 and 52. Thereafter, the laser can be maintained at that wavelength or fine-tuned therefrom by selectively controlling the orientation of only the etalon 48.

As schematically indicated in FIG. 3, a



- 7 -

micropositioner 56 is connected via a mechanical coupler 58 to the etalon 48. In response to signals applied to the micropositioner 56 on line 60, the orientation of the etalon is thereby controlled to maintain the wavelength of the laser beam 55 at a predetermined value or to move the wavelength off that value by a specified amount to accomplish electronic focus tracking. The manner in which the micropositioner 56 is so controlled will be described in detail later below.

Various instrumentalities are known in the art for tuning and line-narrowing the output of a short-wavelength laser as is done by assembly 54. In this connection, see, for example: "Injection-Locked, Narrow-Band KrF Discharge Laser Using an Unstable Resonator Cavity" by J. Goldhar et al, Optics Letters, Vol. 1, No. 6, December 1977, pp. 199-201; "Operating and Beam Characteristics, Including Spectral Narrowing, of a TEA Rare-Gas Halide Excimer Laser" by T. J. McKee et al, IEEE Journal of Quantum Electronics, Vol. QE-15, No. 5, May 1979, pp. 332-334; "Grazing Angle Tuner for CW Lasers" by K. R. German, Applied Optics, Vol. 20, No. 18, September 15, 1981, pp. 3168-3171; and "A Simple Tunable KrF Laser System with Narrow Bandwidth and Diffraction-Limited Divergence" by R. G. Caro et al, Journal Physics D: Applied Physics, 15, 1982, pp. 767-773.

The aforescribed feedback loops for controlling the galvanometer motors 30 and 32 (FIG. 1) require continuous electrical input signals. But the pulsed laser 12 is not capable of providing such signals via the detector 24 (FIG. 2). Hence, a continuous-wave (CW) laser 62 (for example, a standard helium-neon laser operating at 6328 Å) is also included in the equipment 10. The laser 62 is designed to provide a continuous reference beam that is coaxial with the aforespecified beam at 2484 Å. In turn, the beam at 6328 Å is converted by the detector 24 into continuous electrical signals that are applied to the

- 8 -

feedback loops that respectively control the galvanometer motors 30 and 32.

Whenever the detector 24 senses that the reference beam at 6328 Å is off-center relative to its prescribed alignment with the detector 24, correction signals are applied to the motor 30 and/or to the motor 32 to re-establish the prescribed alignment. And, since the beams at 6328 Å and 2484 Å are propagated coaxially in the equipment 10, these correction signals are effective to re-establish the prescribed alignment of the exposing beam at 2484 Å.

The output of the CW laser 62 (FIG. 1) is directed via a high-reflectivity mirror 64 to a dichroic mirror 66. The mirror 66 is designed to reflect the incident beam at 6328 Å to the right along an X-direction path indicated by arrow 68. The mirror 66 is also designed to transmit most of the incident beam at 2484 Å emanating from the assembly 54 along the same X-direction path. Thus, the arrow 68 indicates the path along which the CW beam at 6328 Å and the pulsed beam at 2484 Å propagate coaxially to successively impinge upon the galvanometer mirrors 20 and 22. After reflection from the mirrors 20 and 22, the coaxial beams are propagated from the equipment 10. These coaxial beams constitute the previously specified beams 18.

A small portion (for example, about one percent) of the beam at 2484 Å emanating from the assembly 54 of FIG. 1 is reflected upward by the mirror 66 along a Y-direction path indicated by arrow 69 to a wavemeter 70. In response thereto, the wavemeter 70 provides an electrical signal to one input of a differential amplifier 72. The other input to the amplifier 72 is supplied by the control computer 38. In that way, the output of the amplifier 72 applied to the lead 60 is effective to maintain the output of the assembly 54 at a predetermined center wavelength specified

- 9 -

by the computer 38. Or, as will be described in more detail later below, the signal applied to the amplifier 72 by the computer 38 can also be utilized to purposely change the center wavelength to achieve electronic focus

5 tracking.

Further, the aforespecified ability of the computer 38 (FIG. 1) to easily control or adjust the center wavelength of the beam emanating from the assembly 54 simplifies the overall design and fabrication of the equipment described herein. This is so because in practice one can rarely make an all-fused-silica lens assembly precisely to a specified prescription. Normally, one would have to install the fabricated lens assembly in the equipment, test the assembly at a prespecified center  
10 frequency, and then take the assembly apart to make adjustments therein by further machining, polishing, etc.

Subsequently, re-installation of the lens assembly and further testing in the equipment would be done, and so forth in an interactive fashion until a near-  
15 optimal match between the lens assembly and the center wavelength was obtained. Such mechanical tuning or matching of the lens assembly to a fixed prespecified center wavelength is obviously time-consuming and expensive.

By contrast, in applicant's unique design, it is often possible, after initially installing the all-fused-silica lens assembly in the herein-described equipment, to achieve a near-ideal adjustment of the equipment without removing the lens assembly. This is done by leaving the installed assembly intact and adjusting the center  
20 wavelength of the exposing beam, under control of the computer 38, to obtain a near-optimal match between the operating characteristics of the lens assembly as initially fabricated and the operating wavelength of the equipment. Such electronic, rather than mechanical, adjustment of the  
25 equipment is manifestly advantageous.

The laser beams at 2484 Å and 6328 Å

- 10 -

that emanate from the equipment 10 in the direction of arrow 18 are directed at the equipment 14 shown in FIG. 2. In particular, these beams are directed at a mirror 74 in the equipment 14. The mirror 74 is designed to be highly reflective at 6328 Å and highly transmissive at 2484 Å. As a result, most of the 6328 Å beam is directed to the right in the direction of arrow 76 and most of the 2484 Å beam is directed downward in the direction of arrow 78.

10           The 6328 Å beam propagated in the direction of the arrow 76 in FIG. 2 passes through a filter 80. The filter 80 is designed to pass the 6328 Å beam but to block any portion of the 2484 Å beam that was reflected by the mirror 74 in the direction of the arrow 76. Accordingly, only the CW beam at 6328 Å impinges upon the detector 24. In turn, as described earlier above, the detector 24 provides continuous electrical signals in the feedback loops shown in FIG. 1 to control the operation of the galvanometer motors 30 and 32. In that way, the orientation of the 6328 Å beam 76 relative to the table 16, and thus also the orientation of the coaxially disposed 2484 Å exposing beam 78, are maintained fixed even during vibratory motion of the table 14.

25           The 2484 Å beam propagated downward in FIG. 2 in the direction of the arrow 78 is directed at an adjustable field stop or aperture 82. Illustratively, the diameter of the beam at the stop 82 is designed to be larger than the diameter of the opening in the stop.

30           In practice, the equal-intensity contour lines of the 2484 Å beam transmitted through the stop 82 of FIG. 2 are not symmetrically disposed with respect to the opening in the stop. Moreover, this asymmetry tends to vary from pulse to pulse. If not compensated for, these factors can result in unsatisfactory illumination uniformity and consequent poor linewidth control at the surface of the wafer 40.

- 11 -

In accordance with a feature of the invention, the slightly oversize beam directed at the stop 82 is dithered or moved systematically by small amounts  $\Delta X$  and  $\Delta Z$ . For an exposure that comprises, for example, several  
5 hundred successive laser pulses, such movement is effective to accomplish area averaging of the pulses transmitted through the stop 82. In turn, this results in better illumination uniformity at the surface of the wafer 40.

Movement of the 2484 Å beam 78 directed  
10 at the stop 82 (FIG. 2) to carry out area averaging is controlled by the computer 38 (FIG. 1). Signals applied by the computer 38 via leads 86 and 87 to the galvanometer motors 30 and 32, respectively, are effective to implement the aforementioned  $\Delta Z$  and  $\Delta X$  movements of the beam across  
15 the aperture in the stop 82.

The 2484 Å beam 78 that passes through the stop 82 impinges upon a mirror 88 shown in FIG. 2. This mirror is designed to reflect a relatively small amount (for example about one percent) of the incident  
20 beam. In turn, the reflected portion is directed through a filter 90 to a photodiode 92. The filter 90 is designed to pass light at 2484 Å but to block light at 6328 Å. In that way, any 6328 Å component in the beam transmitted by the stop 82 is prevented from  
25 impinging on the photodiode 92.

The photodiode 92 of FIG. 2 constitutes part of a dose control and laser trigger arrangement. The photodiode 92 samples a portion of each 2484 Å pulse and, in response thereto, generates an electrical  
30 signal that is applied to a light integrator 94 (FIG. 1). The control computer 38 supplies a second input signal (a dose control signal) to the light integrator 94. In turn, the output of the integrator 94 is applied to the laser 12 as a trigger signal therefor.

35 The operation of the dose control and laser trigger arrangement is as follows. Under computer control,

- 12 -

the stepping table 16 is moved by a micropositioner 95 to bring a chip site on the resist-coated wafer 40 into position for exposure to the pattern contained on the reticle 84. (Illustratively, the reticle is assumed to contain a single chip pattern thereon.) The computer 38 then activates the integrator 94 to trigger the laser 12 to start emitting pulses at 2484 Å. A portion of each pulse is sampled by the photodiode 92 and a signal representative thereof is applied to the integrator 94.

When the integrator 94 detects that the prescribed dose set by the computer 38 has been attained, the laser 12 is signaled to cease emitting pulses. Subsequently, the table 16 is moved to position another chip site on the wafer 40 in position for the next exposure.

Exposure is accomplished by projection of illumination through a condenser lens 110, through a reticle 84 containing the pattern to be imaged on the wafer 40, and through a projection lens 108. The provision of a virtual source of illumination for the lens 110 is now described.

As indicated in FIG. 2, the 2484 Å beam 78 that is transmitted through the mirror 88 is directed toward a collimating lens 96. The lens 96 serves to focus the beam to a small spot and to direct it at a mirror or prism element 98. The small spot comprises a first virtual source of illumination. The element 98 is designed to deflect the beam into the edge of the field of a scanning lens assembly 101 represented here by field lens 100 and additional lens elements 102 and 104. In turn, the beam is reflected by a scanning mirror assembly 106 back into the scanning lens assembly 101.

To achieve adequate illumination of the entrance pupil of the projection lens 108 and hence proper imaging characteristics on the wafer 40, it is advantageous to illuminate about 50-to-75 percent of the diameter of the entrance pupil of the lens 108. Illustratively, the entrance pupil of the lens 108, as defined by an aperture

- 13 -

stop 109 (shown schematically in FIG. 2), is approximately 100 millimeters in diameter. It is apparent, therefore, that simply relaying the small first virtual source to the lens 108 will not in practice provide adequate illumination of the entrance pupil of the lens 108.

In accordance with one aspect of the invention, the effective size of the virtual source that is actually relayed to the projection lens 108 is substantially increased in size over that of the first virtual source produced by the lens 96. This is done by means of the scanning lens assembly 101 and the scanning mirror assembly 106. By means of these assemblies, the operation of which is described hereinafter, both the size and shape of the effective virtual source can be selectively varied under control of signals applied to the assembly 106 from the computer 38. Significantly, in the course of making such variations, no laser light at  $2484 \text{ \AA}$  is wasted in the depicted equipment. Hence, all available exposing light is delivered to the surface of the wafer 40 even as changes are made in the size and shape of the illumination relayed to the entrance pupil of the projection lens 108.

The ability to change both the size and shape of the illuminated portion of the entrance pupil of the projection lens 108 can be significant in that it allows, for example, tailoring the illumination to optimize resolution of certain critical features on the wafer 40 and to take maximum advantage of any nonlinearities in the characteristics of the resist layer on the wafer 40.

The scanning mirror assembly 106 schematically depicted in FIG. 2 comprises a mirror 112 and two independently rotatable shafts 114 and 116. The shaft 114 is oriented parallel to the X axis, whereas the shaft 116 is oriented perpendicular to the X axis. Rotation back and forth of the shaft 116 causes the mirror 112 to rock back and forth, as indicated by double-headed arrow 118. At the same time that rocking occurs, the shaft 114 is turning, as indicated by arrow 120. In other words, as the mirror

- 14 -

rocks in response to rotation of the shaft 116, the rocking mirror is independently rotated by the shaft 114. As a consequence, a relatively large area A in a Y-Z plane immediately to the left of the lens 100 can be

5 substantially filled with the successive pulses supplied by the laser 12 of FIG. 1 to form a large-area virtual source. Illustratively, several hundred successive pulses are supplied by the laser 12 during each interval in which a chip site on the wafer 40 is being exposed.

10 The size of the aforespecified large-area virtual source can be changed by varying the extent to which the mirror 112 is rocked by the shaft 116. Additionally, the shape of the virtual source can be changed by varying the speed of rotation of the shaft 114 while the mirror 112 is  
15 being rocked.

Light emanating from the relatively large-area virtual source formed to the left of the lens 100 (FIG. 2) is directed by the relay lens 110 to illuminate the pattern contained on the reticle 84. In turn, light propagated  
20 through the reticle 84 is imaged by the lens 109 onto a chip site on the surface of the wafer 40. Illustratively, the lens 109 forms a reduced (for example 5-to-1 reduced) version of the reticle pattern on the wafer surface.

In a standard exposure system, conventional focus  
25 tracking is accomplished by mechanically changing the projection lens-to-wafer distance. Typically, this is done either by moving the optical column of the system or by moving the wafer. In either case, the adjustment is time-consuming and, moreover, may cause undesirable mechanical  
30 resonances in the system.

In accordance with one aspect of the present invention, focus tracking is carried out quickly in a nonmechanical manner. The ability to do so stems from the use of lenses made from a single optical material. Such  
35 lenses, unlike those corrected for chromatic aberrations, exhibit an approximately linear relationship between wavelength and focal distance. Hence, by electronically



- 15 -

changing the wavelength of the laser 12 (FIG. 1), the focal plane of the projection lens 108 (FIG. 2) is also changed.

The operation of the focus tracking arrangement is as follows. First, a standard focus sensor 111 detects whether or not the distance between the projection lens 108 and the surface of the wafer 40 has changed from a prespecified value. Assume, for example, that that distance has changed (decreased) by one micron, due, for example, to warpage in the wafer 40. A signal representative of the change is then sent to the computer 38 via lead 122. In response thereto, the computer applies a corresponding correction signal to the differential amplifier 72 (FIG. 1) included in the aforescribed frequency control loop. In turn, a signal is applied by the amplifier 72 to the tuning and line-narrowing assembly 54 to increase the center wavelength of the pulses emanating from the assembly 54. In one illustrative case, the center wavelength was increased by 0.1 Å. This was sufficient to decrease the focal distance of the lens 108 by one micron, thereby to compensate exactly for the assumed one-micron decrease in the lens-to-wafer spacing.

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- 16 -

Claims

1. Apparatus for optical lithography,  
CHARACTERIZED BY  
means (12, 54) for providing narrow-  
5 bandwidth laser radiation,  
and a lens assembly (101, 106, 108, 110)  
made of a single optical material disposed in the path of  
said radiation and exhibiting substantially no chromatic  
aberrations in response thereto.
- 10 2. Apparatus as in claim 1 wherein said single  
optical material consists of fused silica.
3. Apparatus as in claim 2 wherein said  
providing means comprises  
a pulsed laser (12),  
15 and a tuning and bandwidth-narrowing  
assembly (54) responsive to the output of said laser for  
supplying narrow-bandwidth pulses.
4. Apparatus as in claim 3 further comprising  
a laser (62) for providing a continuous-wave  
20 signal,  
means (55, 64) for coaxially propagating  
said laser pulses and said laser signal, a two-dimensional  
scanning assembly (20, 22) for deflecting said coaxially  
propagated pulses and signal, and  
25 means (24) responsive to said deflected  
laser signal for detecting any deviation thereof from a  
prescribed alignment and for applying correction signals to  
said scanning assembly to maintain the prescribed alignment  
of said laser signal and thus also of said coaxially  
30 propagated laser pulses.
5. Apparatus as in claim 4 further including  
a field stop (82) disposed in the path of  
said aligned laser pulses, said stop including an aperture  
whose diameter is less than the cross-sectional diameter of  
35 the pulses directed thereat, and  
computer control means (38) for applying  
signals to said scanning assembly to cause said laser

- 17 -

pulses to be systematically scanned across the aperture in said stop to achieve area averaging of the intensity profile of pulses transmitted through said aperture.

5 6. Apparatus as in claim 5 further including a light integrator (94) for measuring the cumulative energy delivered by said laser pulses during a cycle of operation of said apparatus and terminating said cycle when the total energy delivered exceeds a preselected threshold value.

10 7. Apparatus as in claim 5 further including a scanning lens assembly (101), a scanning mirror assembly (106), and means (98) for projecting said pulses via said scanning lens assembly to said scanning mirror assembly for forming an enlarged virtual source composed of  
15 successive ones of said pulses.

8. Apparatus for optical lithography or characterized by  
a tunable laser (12) for providing a light beam,  
20 means responsive to the center wavelength of said light beam for projecting said light beam to a focal plane supposedly coplanar with the surface of a workpiece, means for detecting any spacing between the focal plane of the projected beam and the surface of the  
25 workpiece for providing a correction signal, and means responsive to the correction signal for varying the center wavelength of the laser to move the focal plane of the projected beam to eliminate said spacing.

30 9. Apparatus as in claim 8 in which the tunable laser is an excimer laser whose center wavelength is in the deep ultraviolet and the projecting means includes a fused silica lens assembly.

35 10. Apparatus for optical lithography, comprising

a laser source (12) and a workpiece support table (16) movable relative to said source,

- 18 -

characterized by

means (54, 20, 22, 74, 24) for directing  
signals from said laser source to said table to maintain a  
prescribed alignment between the direction of propagation  
5 of said signals and said table during movement of said  
table.

11. Apparatus as in claim 10 wherein said  
directing means comprises

photodetector means (24) responsive to laser  
10 signals from said source for generating electrical signals  
representative of said alignment,

and deflection means (54, 20, 22) responsive  
to said electrical signals for controlling the direction of  
propagation of said laser signals.

12. A method of maintaining the output beam of a  
15 laser aligned relative to movable equipment at which the  
beam is directed, said method characterized by the steps  
of

directing said beam at a photodetector array  
20 mounted on said movable equipment, said array generating  
electrical signals representative of variations of said  
beam relative to a prescribed alignment with said array,  
and applying said electrical signals via a  
feedback loop to a deflection assembly to maintain said  
25 beam aligned with said array.

13. A method as in claim 12 wherein said laser  
beam comprises laser pulses and a continuous-wave laser  
signal propagated coaxially with said pulses, said array  
being responsive only to said continuous-wave signal for  
30 generating continuous electrical signals in said feedback  
loop.

14. A method of defining fine-line features on a  
wafer, said method characterized by the steps of  
generating narrow-bandwidth laser pulses,  
35 directing said pulses via a lens and  
scanning assembly to form an enlarged virtual source  
composed of said multiple pulses, and

- 19 -

projecting said virtual source through a  
reticle onto the surface of said wafer.

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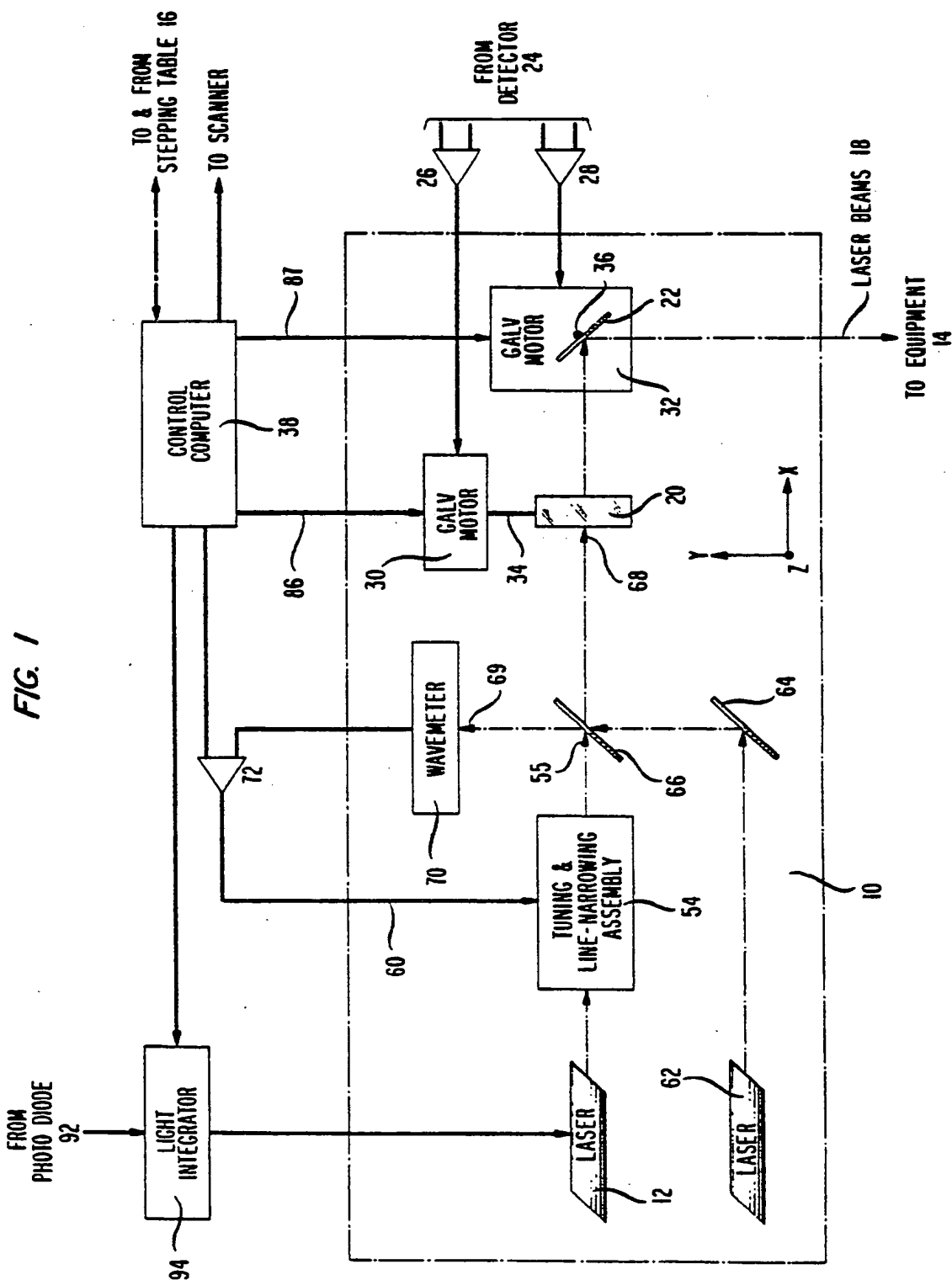
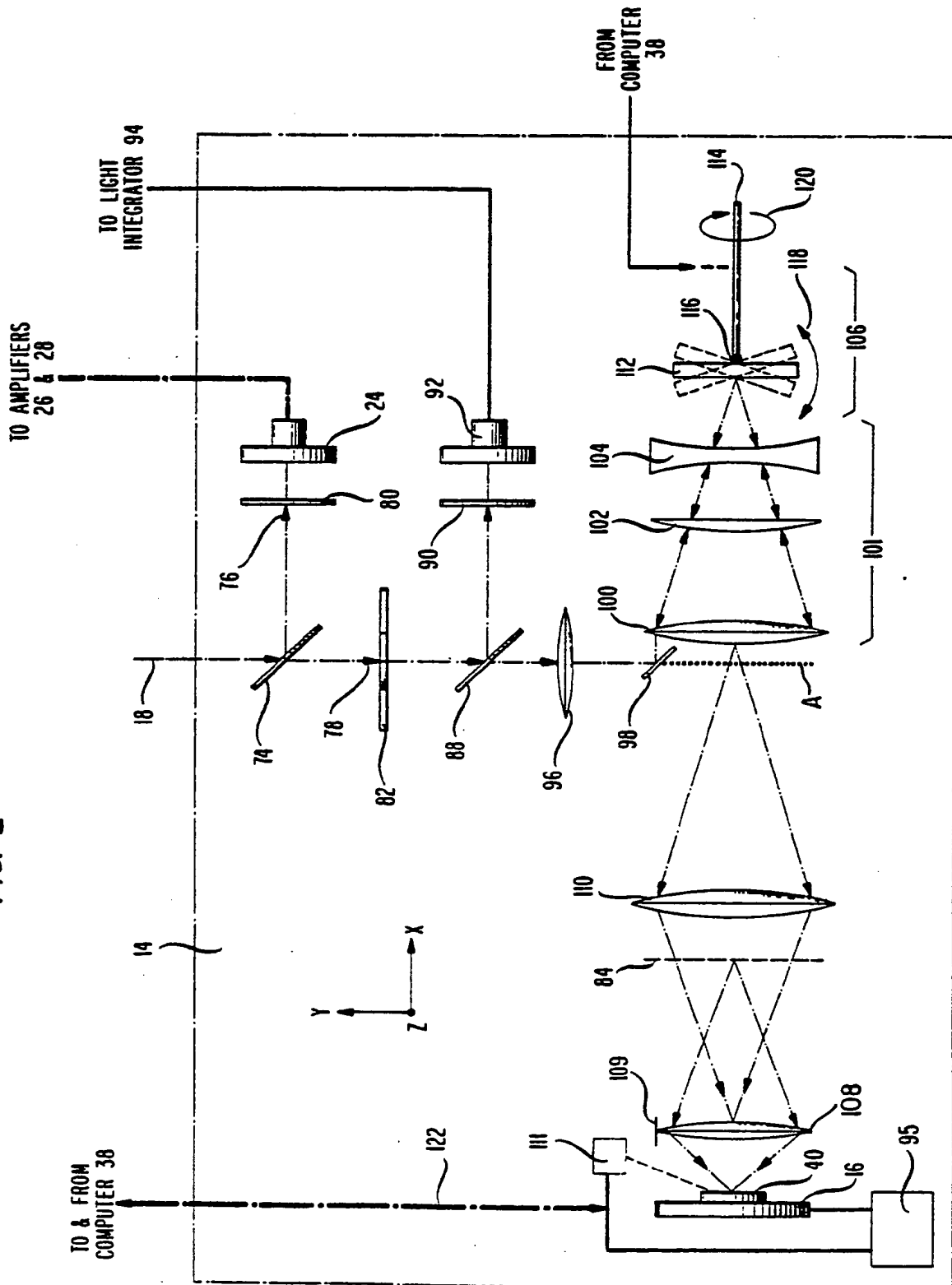
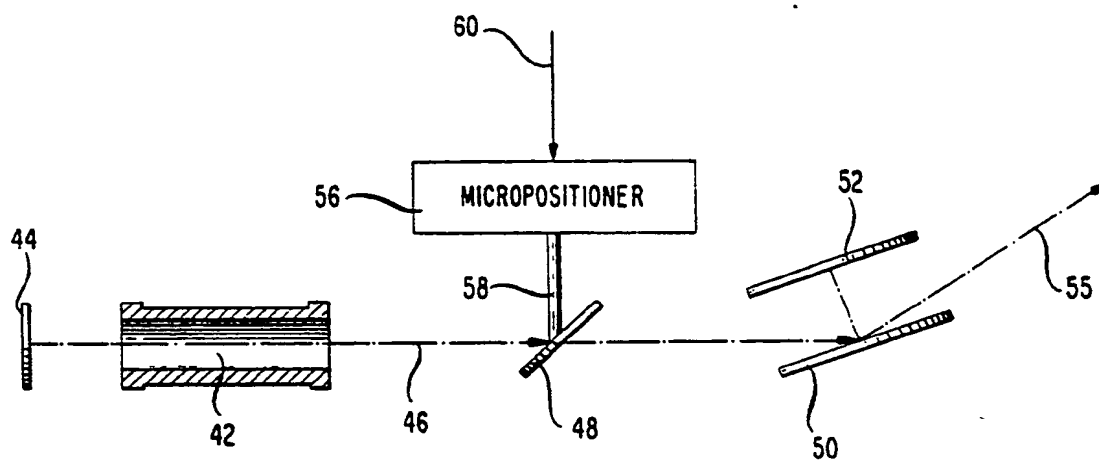


FIG. 2



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FIG. 3





# INTERNATIONAL SEARCH REPORT

International Application No PCT/US 85/01110

<b>I. CLASSIFICATION OF SUBJECT MATTER</b> (if several classification symbols apply, indicate all) * According to International Patent Classification (IPC) or to both National Classification and IPC IPC <sup>4</sup> : G 03 F 7/20; G 02 B 27/00																				
<b>II. FIELDS SEARCHED</b> <div style="text-align: center; margin-top: 10px;">Minimum Documentation Searched <sup>7</sup></div> <table style="width: 100%; border-collapse: collapse;"> <tr> <th style="width: 25%; border-bottom: 1px solid black;">Classification System</th> <th style="width: 75%; border-bottom: 1px solid black;">Classification Symbols</th> </tr> <tr> <td style="border-right: 1px solid black; padding: 5px;">IPC<sup>4</sup></td> <td style="padding: 5px;">G 03 F G 02 B</td> </tr> </table> <div style="text-align: center; margin-top: 10px;">Documentation Searched other than Minimum Documentation to the extent that such Documents are included in the Fields Searched <sup>8</sup></div>			Classification System	Classification Symbols	IPC <sup>4</sup>	G 03 F G 02 B														
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<b>III. DOCUMENTS CONSIDERED TO BE RELEVANT <sup>9</sup></b> <table style="width: 100%; border-collapse: collapse;"> <tr> <th style="width: 10%; border-bottom: 1px solid black;">Category <sup>9</sup></th> <th style="width: 70%; border-bottom: 1px solid black;">Citation of Document, <sup>11</sup> with indication, where appropriate, of the relevant passages <sup>12</sup></th> <th style="width: 20%; border-bottom: 1px solid black;">Relevant to Claim No. <sup>13</sup></th> </tr> <tr> <td style="text-align: center; vertical-align: top; padding: 5px;">Y</td> <td style="padding: 5px;">EP, A, 0066053 (IBM CORP.) 8 December 1982, see page 4, line 8 - page 6, line 35; figures 1-3</td> <td style="text-align: center; vertical-align: top; padding: 5px;">1</td> </tr> <tr> <td style="text-align: center; vertical-align: top; padding: 5px;">A</td> <td style="text-align: center; vertical-align: top; padding: 5px;">--</td> <td style="text-align: center; vertical-align: top; padding: 5px;">9, 14</td> </tr> <tr> <td style="text-align: center; vertical-align: top; padding: 5px;">Y</td> <td style="padding: 5px;">Solid State Technology, volume 25, nr. 5, May 1982, (New York, US) J.D. Buckley: "Expanding the horizons of optical projection lithography", pages 77-82; see the whole document</td> <td style="text-align: center; vertical-align: top; padding: 5px;">1</td> </tr> <tr> <td style="text-align: center; vertical-align: top; padding: 5px;">A</td> <td style="padding: 5px;">Proceedings, seventh Biennial Cornell Electrical Engineering Conference "Active micro- wave semiconductor devices and circuits", held at Cornell University, New York, 14-16 August 1979, J.R. Moulic et al. (IBM); "Submicron photo- lithography using tunable dye lasers", see pages 55-61</td> <td style="text-align: center; vertical-align: top; padding: 5px;">3, 5, 6, 8, 10, 11</td> </tr> <tr> <td style="text-align: center; vertical-align: top; padding: 5px;">A</td> <td style="padding: 5px;">IEEE Journal of Quantum Electronics, volume QE-15, nr. 5, May 1979, page 332</td> <td></td> </tr> </table>			Category <sup>9</sup>	Citation of Document, <sup>11</sup> with indication, where appropriate, of the relevant passages <sup>12</sup>	Relevant to Claim No. <sup>13</sup>	Y	EP, A, 0066053 (IBM CORP.) 8 December 1982, see page 4, line 8 - page 6, line 35; figures 1-3	1	A	--	9, 14	Y	Solid State Technology, volume 25, nr. 5, May 1982, (New York, US) J.D. Buckley: "Expanding the horizons of optical projection lithography", pages 77-82; see the whole document	1	A	Proceedings, seventh Biennial Cornell Electrical Engineering Conference "Active micro- wave semiconductor devices and circuits", held at Cornell University, New York, 14-16 August 1979, J.R. Moulic et al. (IBM); "Submicron photo- lithography using tunable dye lasers", see pages 55-61	3, 5, 6, 8, 10, 11	A	IEEE Journal of Quantum Electronics, volume QE-15, nr. 5, May 1979, page 332	
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<div style="display: flex; justify-content: space-between;"> <div style="width: 48%;"> <p><sup>10</sup> Special categories of cited documents:</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="width: 48%;"> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&amp;" document member of the same patent family</p> </div> </div>																				
<b>IV. CERTIFICATION</b> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%; border-bottom: 1px solid black; padding: 5px;">Date of the Actual Completion of the International Search</td> <td style="width: 50%; border-bottom: 1px solid black; padding: 5px;">Date of Mailing of this International Search Report</td> </tr> <tr> <td style="border-bottom: 1px solid black; padding: 5px;">20th September 1985</td> <td style="border-bottom: 1px solid black; padding: 5px;">23 OCT. 1985</td> </tr> <tr> <td style="border-bottom: 1px solid black; padding: 5px;">International Searching Authority</td> <td style="border-bottom: 1px solid black; padding: 5px;">Signature of Authorized Officer</td> </tr> <tr> <td style="padding: 5px;">EUROPEAN PATENT OFFICE</td> <td style="padding: 5px;">            G. J. M. denenberg         </td> </tr> </table>			Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report	20th September 1985	23 OCT. 1985	International Searching Authority	Signature of Authorized Officer	EUROPEAN PATENT OFFICE	G. J. M. denenberg										
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III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
	T.I. McKee et al.: "Operating and Beam characteristics including spectral narrowing of a tea raregas halide excimer laser", see whole document (cited in the application) --	1,3,14
A	Applied Optics, volume 20, nr. 18, 15 September 1981 K.R. Berman: "Grazing Angle Tuner for CW Lasers", pages 3168-3171, see the whole document (cited in the application) --	
A	EP, A, 0019778 (IBM CORP.) 10 December 1980, see page 1, lines 20-30; page 3, lines 27-33; claims --	5
A	EP, A, 0111128 (IBM CORP.) 20 June 1984, see page 5, lines 21-27; page 8, line 30 - page 9, line 26 --	3,9,14
A	2087 Elektronik, volume 32, nr. 21, October 1983, (Munich, West Germany) page 24; "Laser-Belichtung verkürzt Leiterplatten-Produktion", see whole document --	4,7,11
A	8179 IEEE Electron Devices Letters, volume EDL-3, nr. 3, March 1982, (New York, US) Jain, Willson & Lin: "Ultrafast deep UV lithography with excimer Lasers", pages 53-55, see whole document	

# ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO. PCT/US 85/01110 (SA 9871)

This Annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 08/10/85

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A- 0066053	08/12/82	JP-A- 57198631	06/12/82
		AU-A- 8189882	02/12/82
		US-A- 4458994	10/07/84
		CA-A- 1173889	04/09/84
EP-A- 0019778	10/12/80	JP-A- 55161209	15/12/80
		US-A- 4304467	08/12/81
		CA-A- 1119028	02/03/82
EP-A- 0111128	20/06/84	US-A- 4414059	08/11/83
		JP-A- 59105638	19/06/84

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